Laboratory demonstrations of high-contrast coronagraphic imaging

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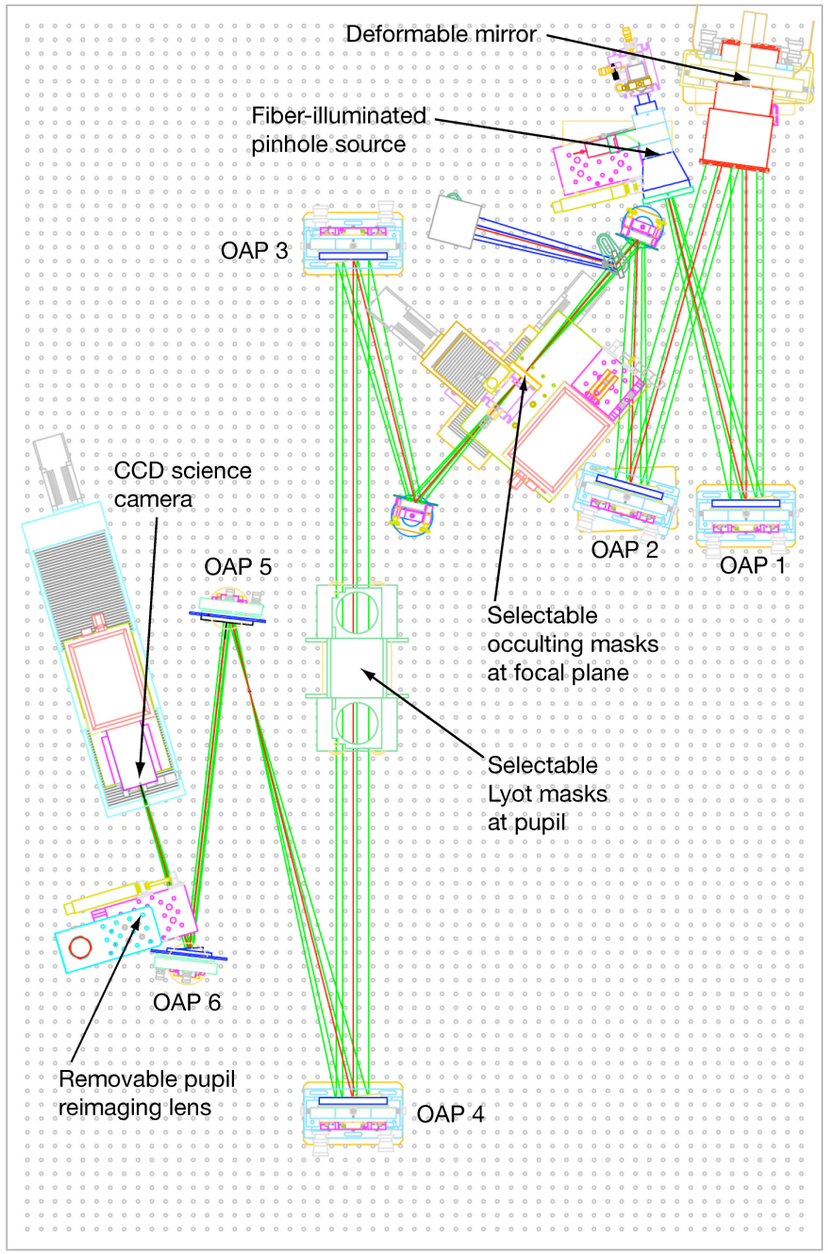
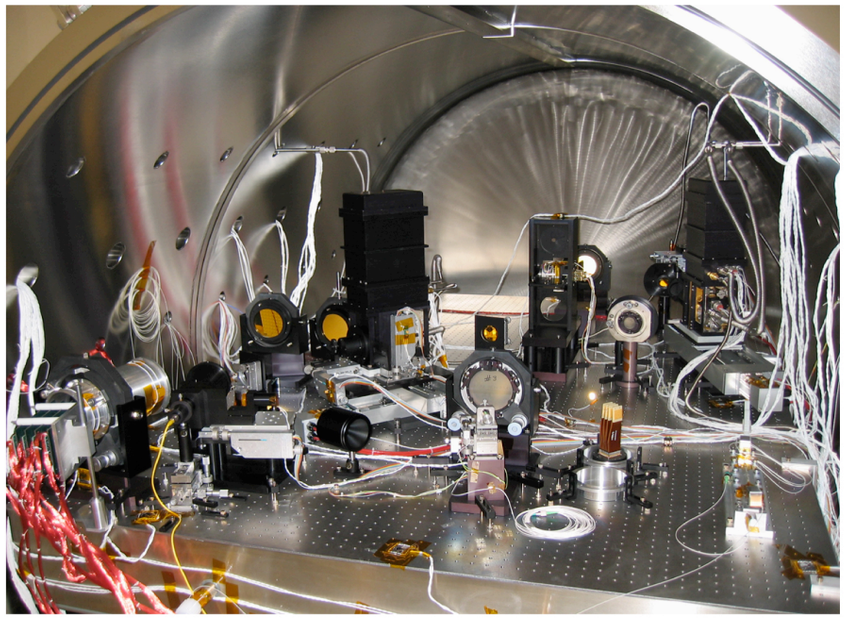
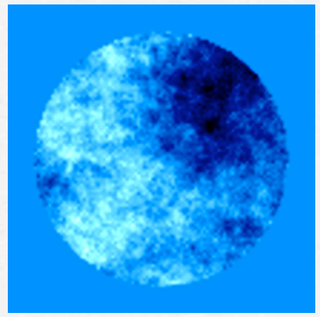
The High Contrast Imaging testbed (HCIT) at JPL



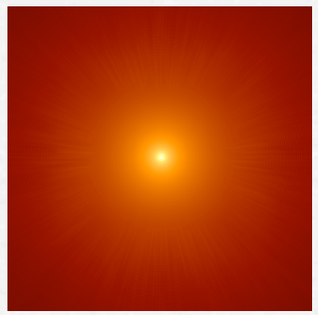


The HCIT captures the essential elements of a space coronagraph with minimal optics

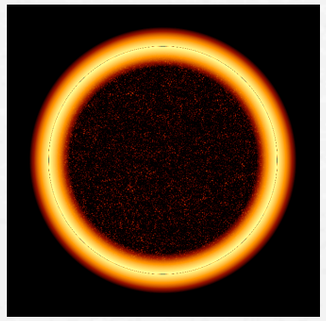
Uncorrected wavefront



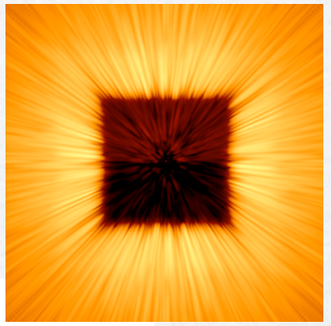
Corrected star image

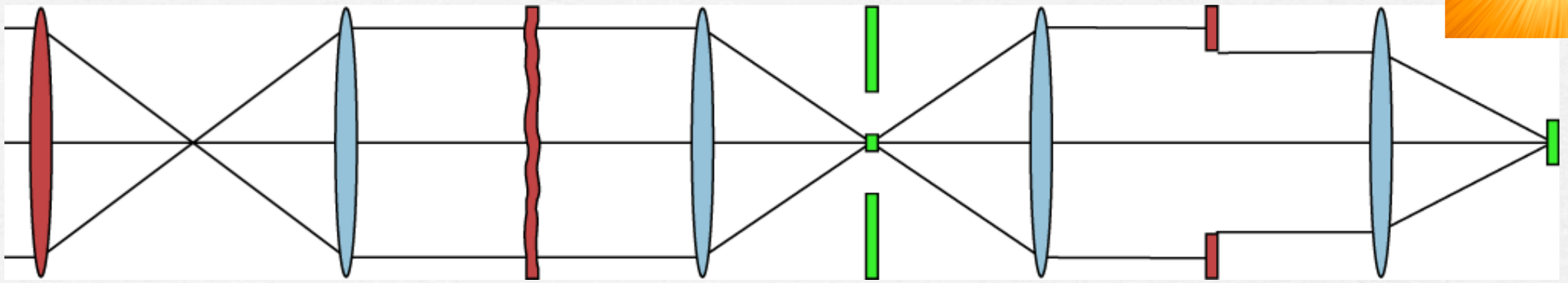


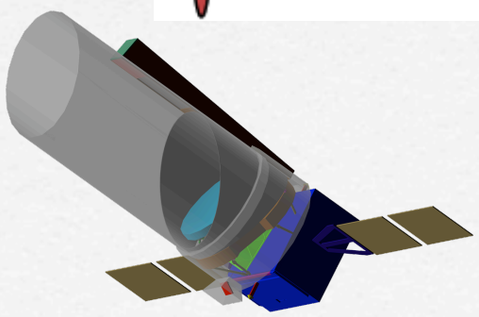
Illumination at pupil plane

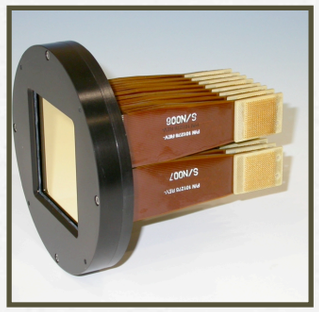


High contrast coronagraphic field

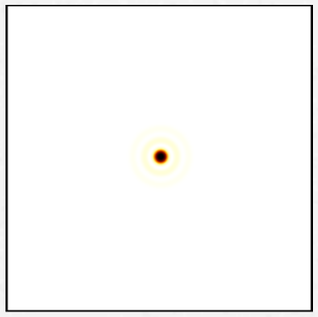








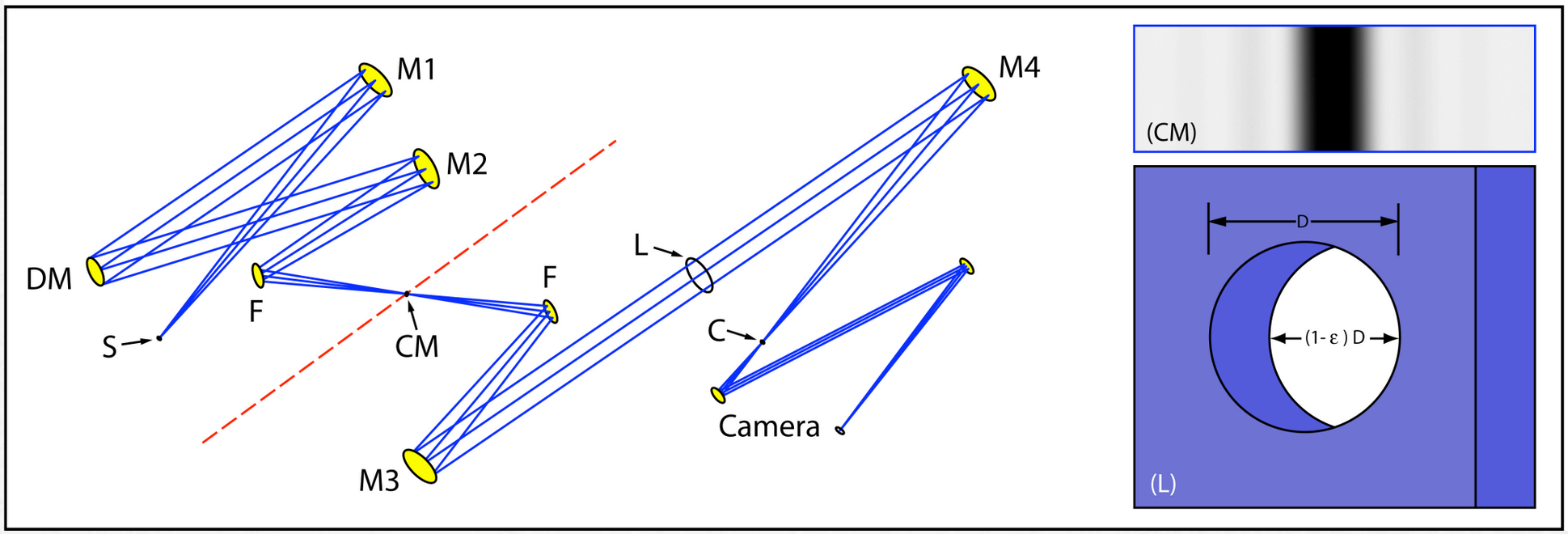
Deformable mirror



Occulting mask

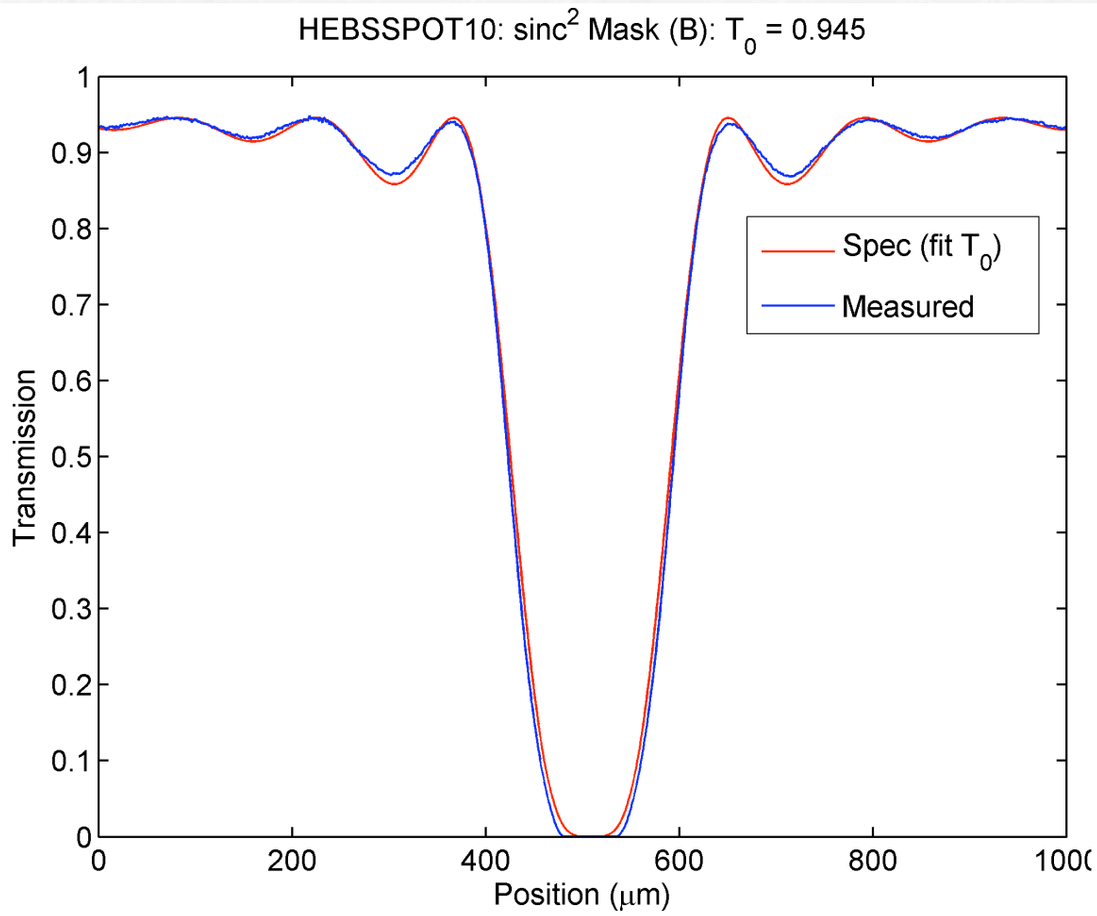
Lyot mask

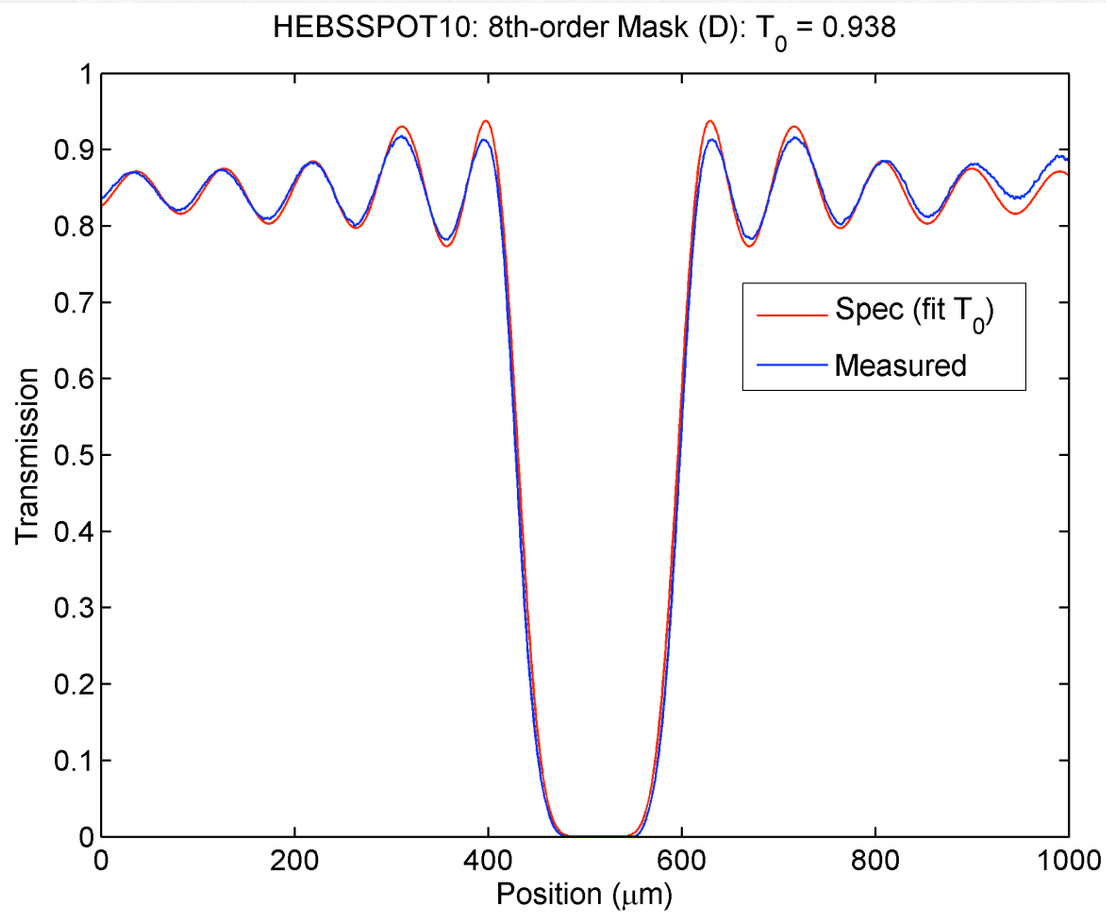
HCIT coronagraph layout



Elements of the HCIT Lyot coronagraph: the light source (S) is a 5 micron pinhole illuminated by light relayed from a fiber; four identical off-axis paraboloidal mirrors (M1, 2, 3, 4); two flat fold mirrors (F), the band-limited focal plane mask (CM); the Lyot mask (L); the high-contrast coronagraph field appears at (C); and the CCD camera with a pair of OAP mirrors for 3x magnification.

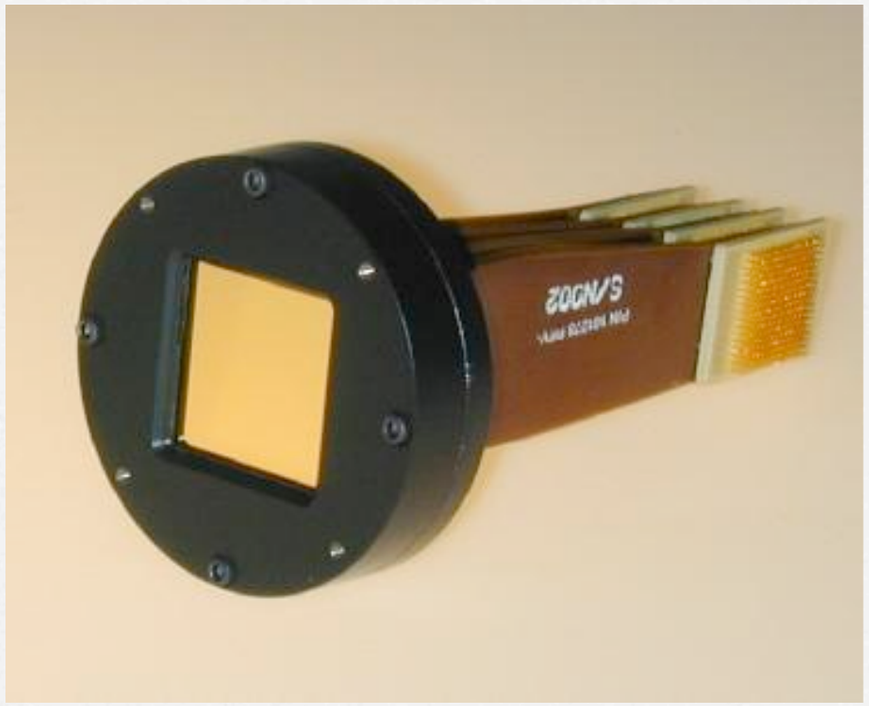
Measured occulter profiles



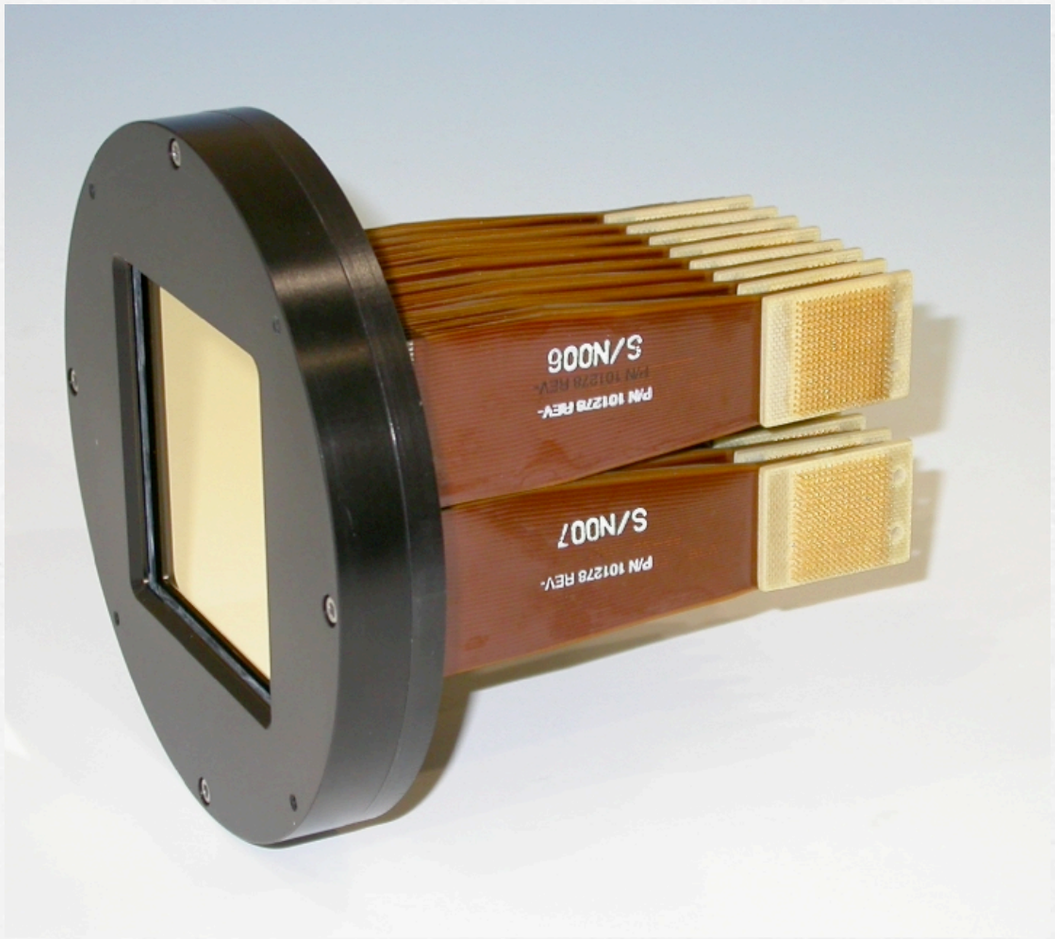


Linear 4th-order (left) and 8th-order (right) masks written in HEBS glass (Canyon Materials) at JPL's Microdevices Laboratory. Transmittance profiles have been measured under a microscope and compared with their respective analytic prescriptions.

Active wavefront correction with a Deformable Mirror (DM)



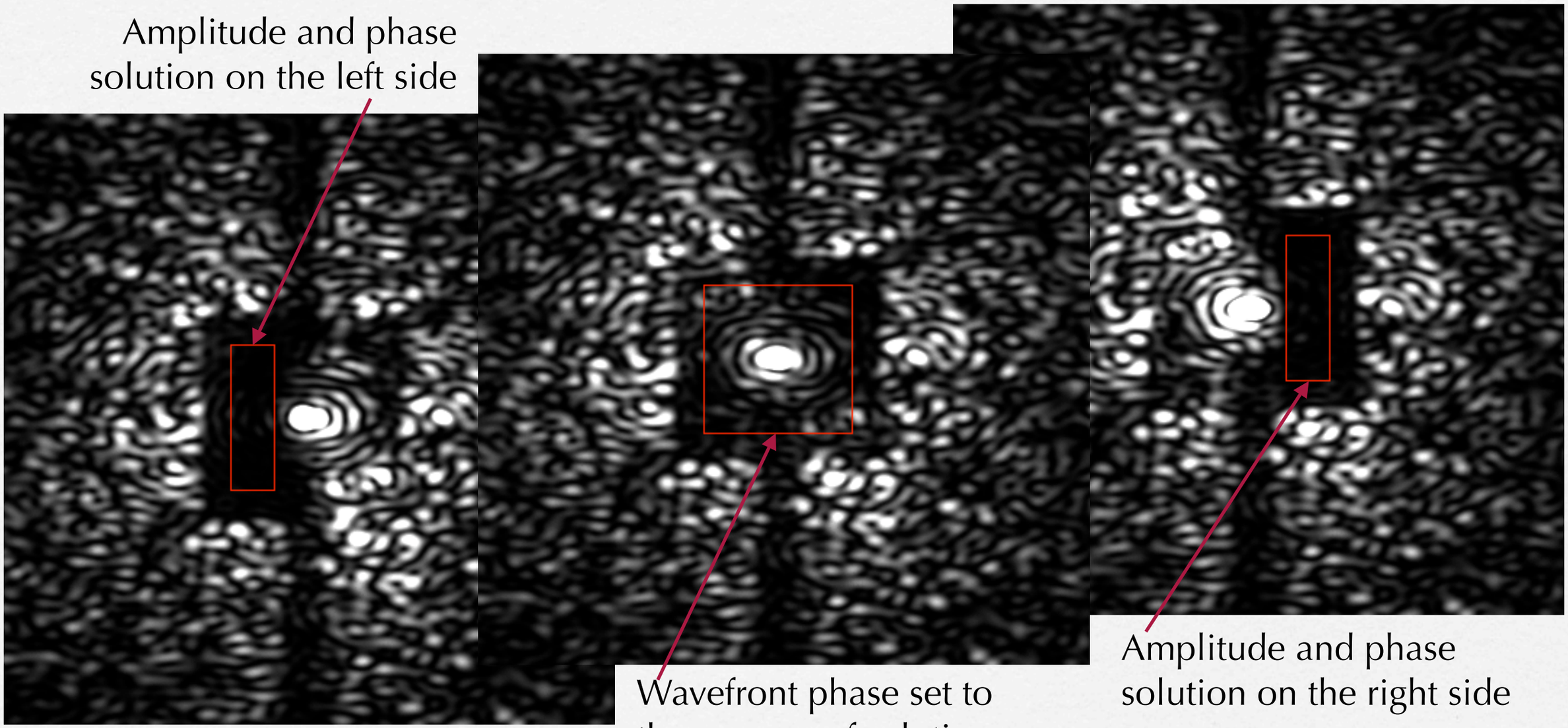
Fifth in a series of Gen2 32x32 mm DMs delivered to JPL by Xinetics. DM surface is polished to λ/100 rms. Active figure control is better than 0.01 nm rms.



Gen2 64x64 mm DM delivered to JPL. The same 32x32 actuator technology is repeated four times, bonded together, with a single facesheet.

Active wavefront correction with a Deformable Mirror (DM)

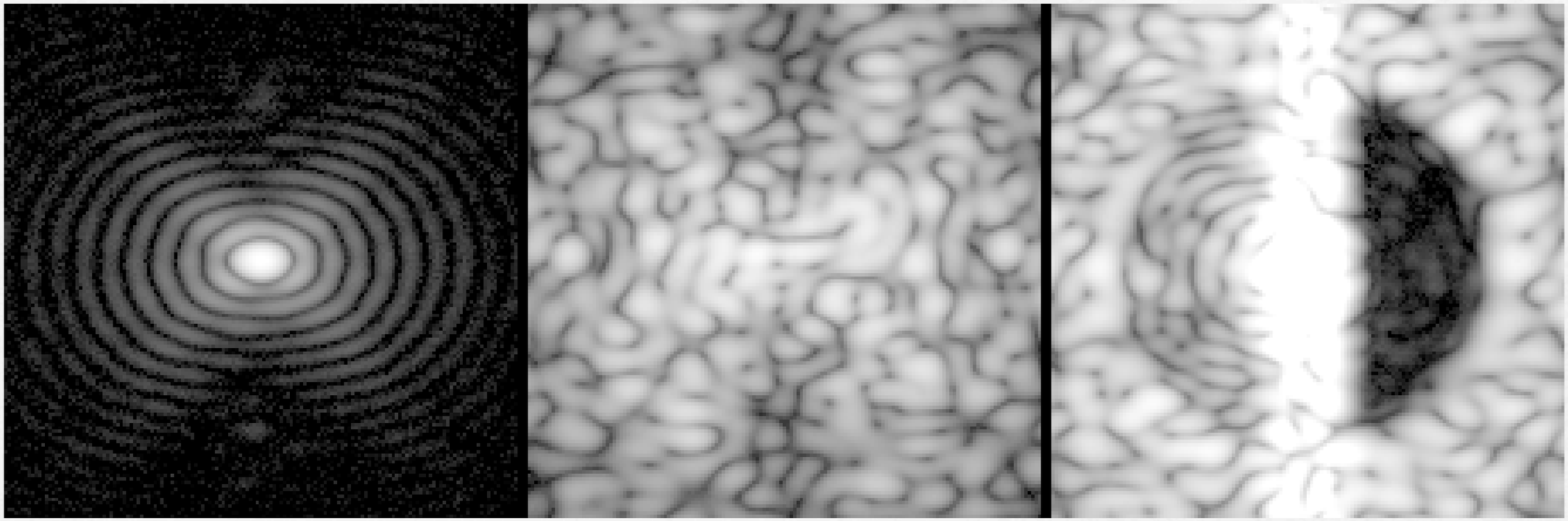
Amplitude and phase solution on the left side



Wavefront phase set to the average of solutions on left and right

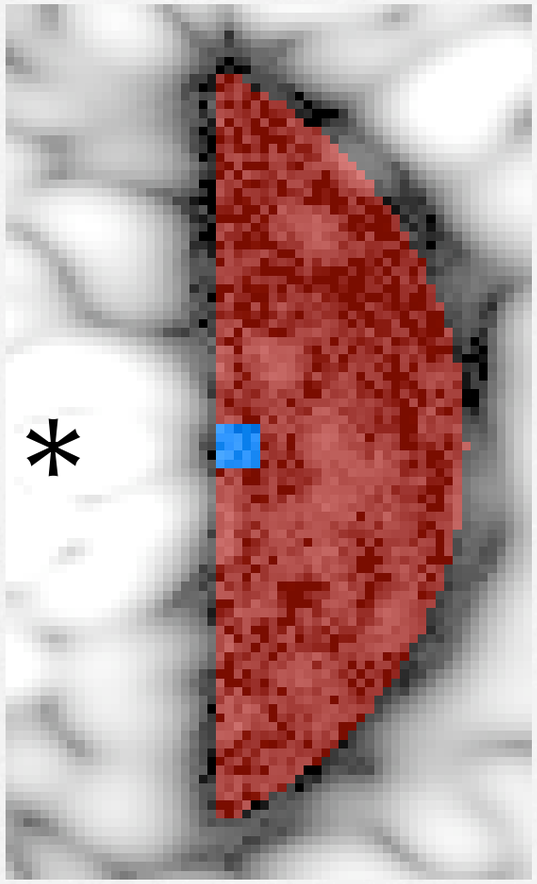
Amplitude and phase solution on the right side

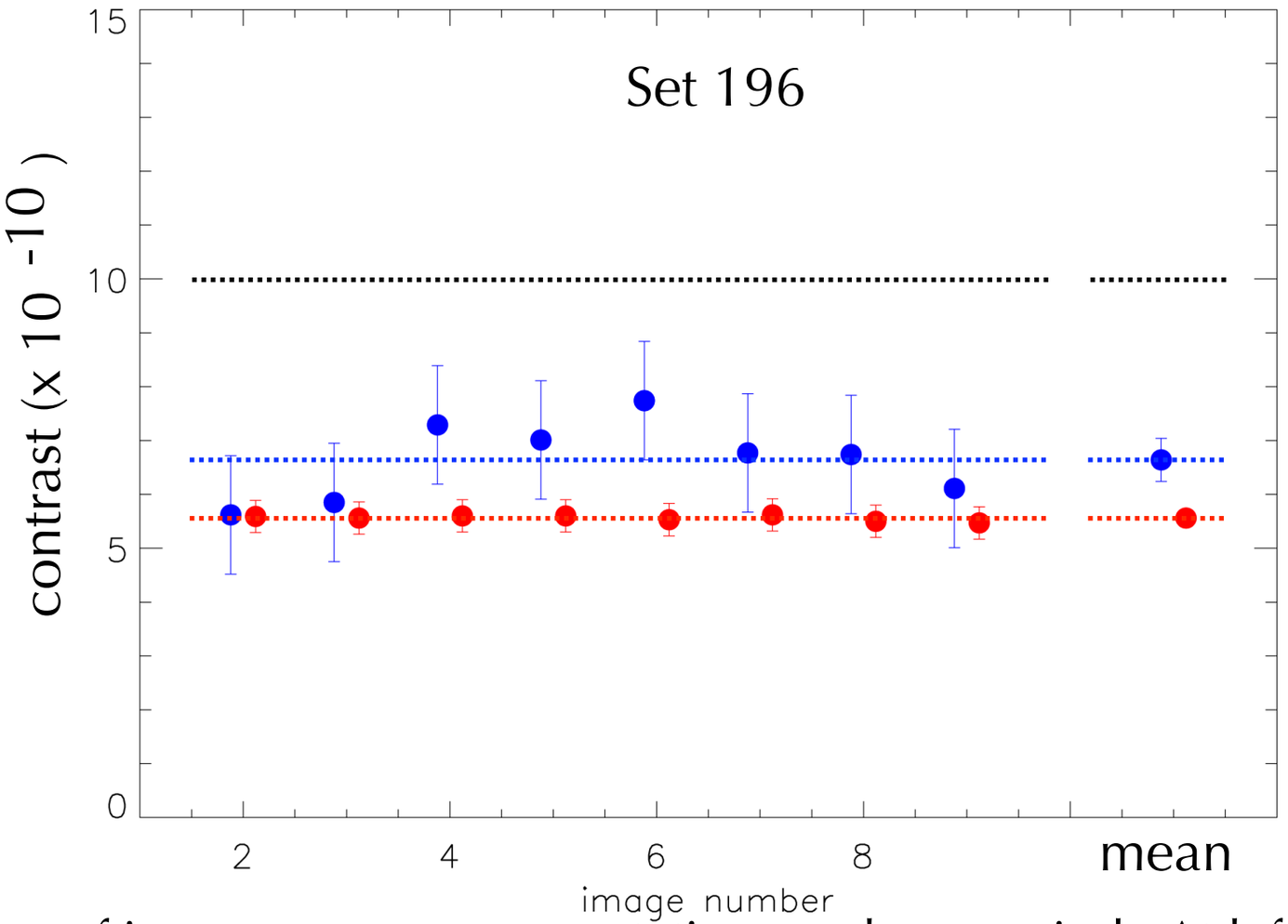
Comparison of coronagraph PSFs



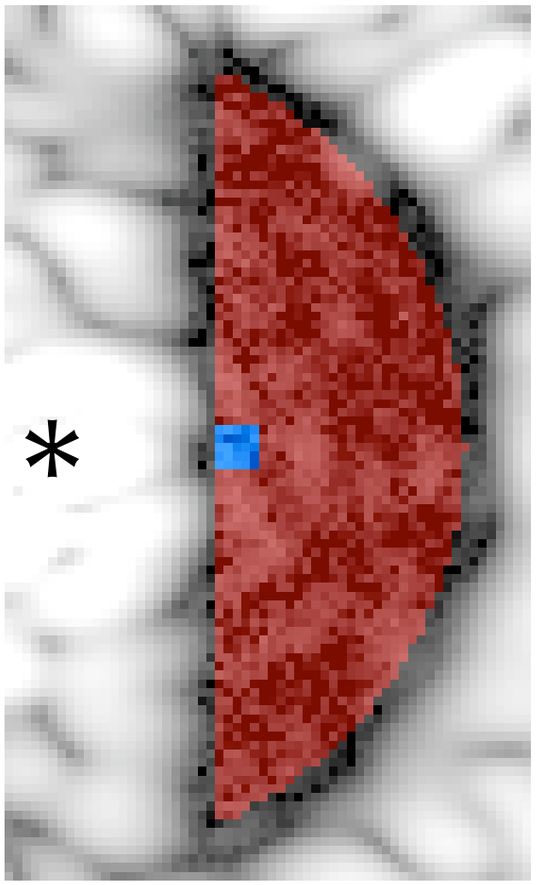
HCIT coronagraph PSFs (contrast stretch is logarithmic). At left is the "star" image obtained with the focal-plane mask removed and Lyot mask in place. At center is the uncorrected coronagraph field with all DM actuators set to 15 volts. At right, the dark half-field with DM voltages set by speckle nulling.

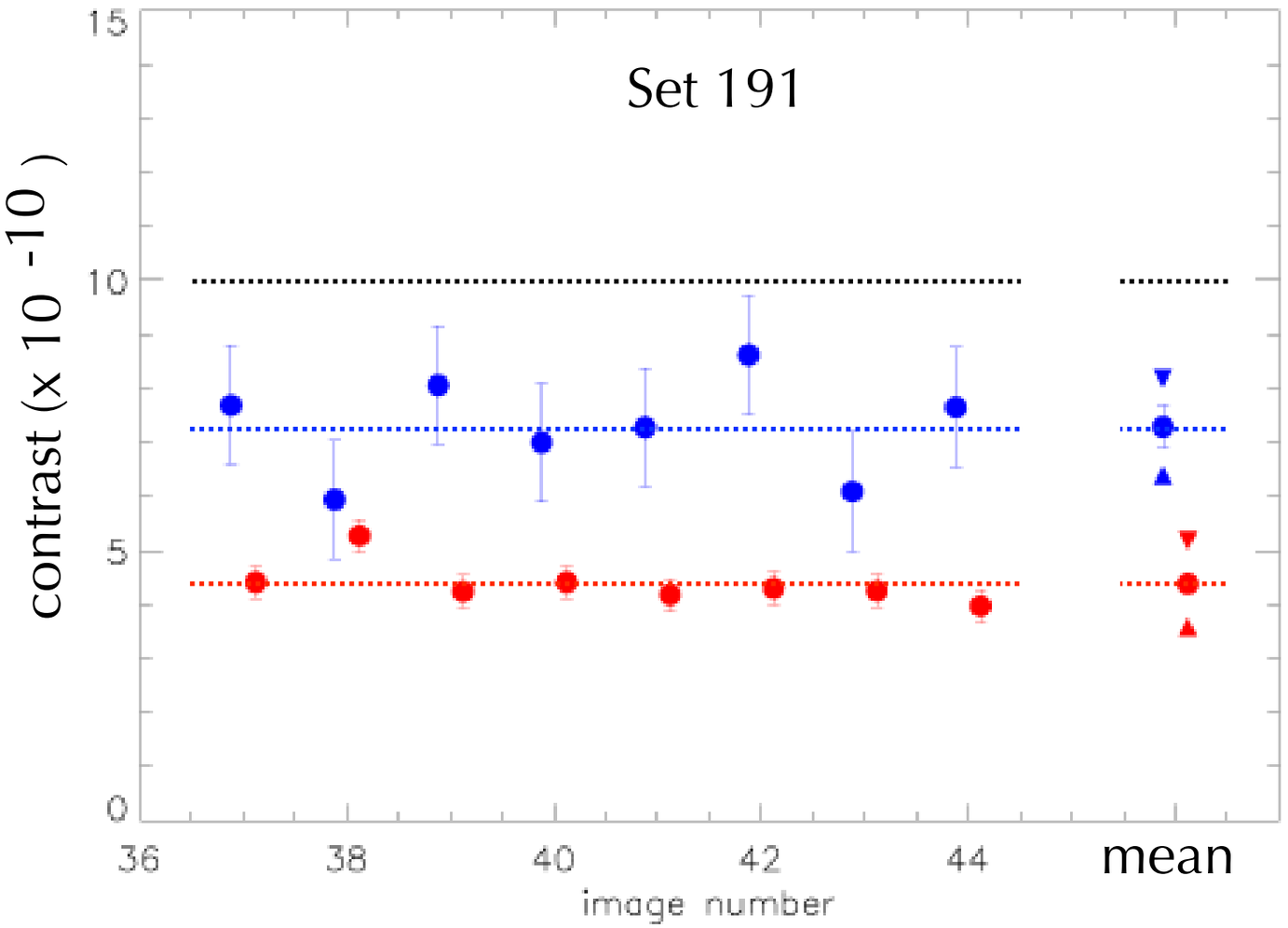
Speckle nulling demonstrations with the HCIT

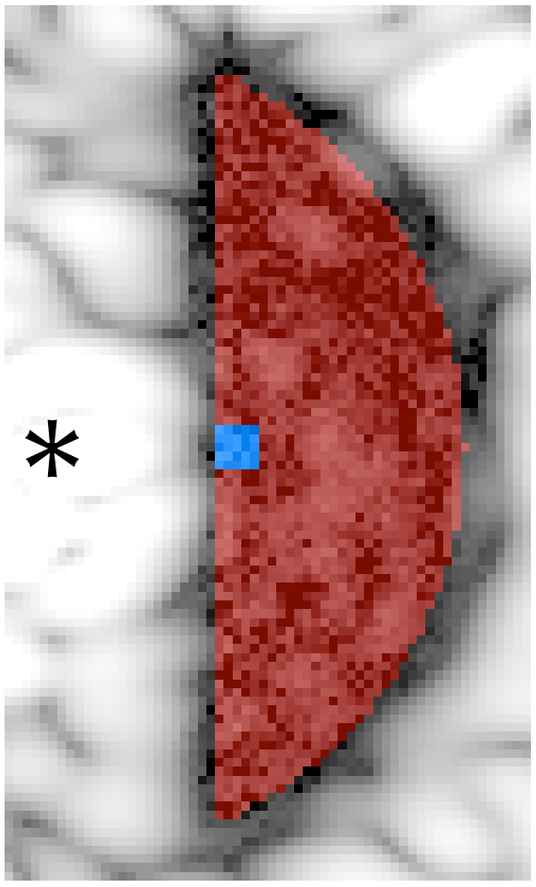


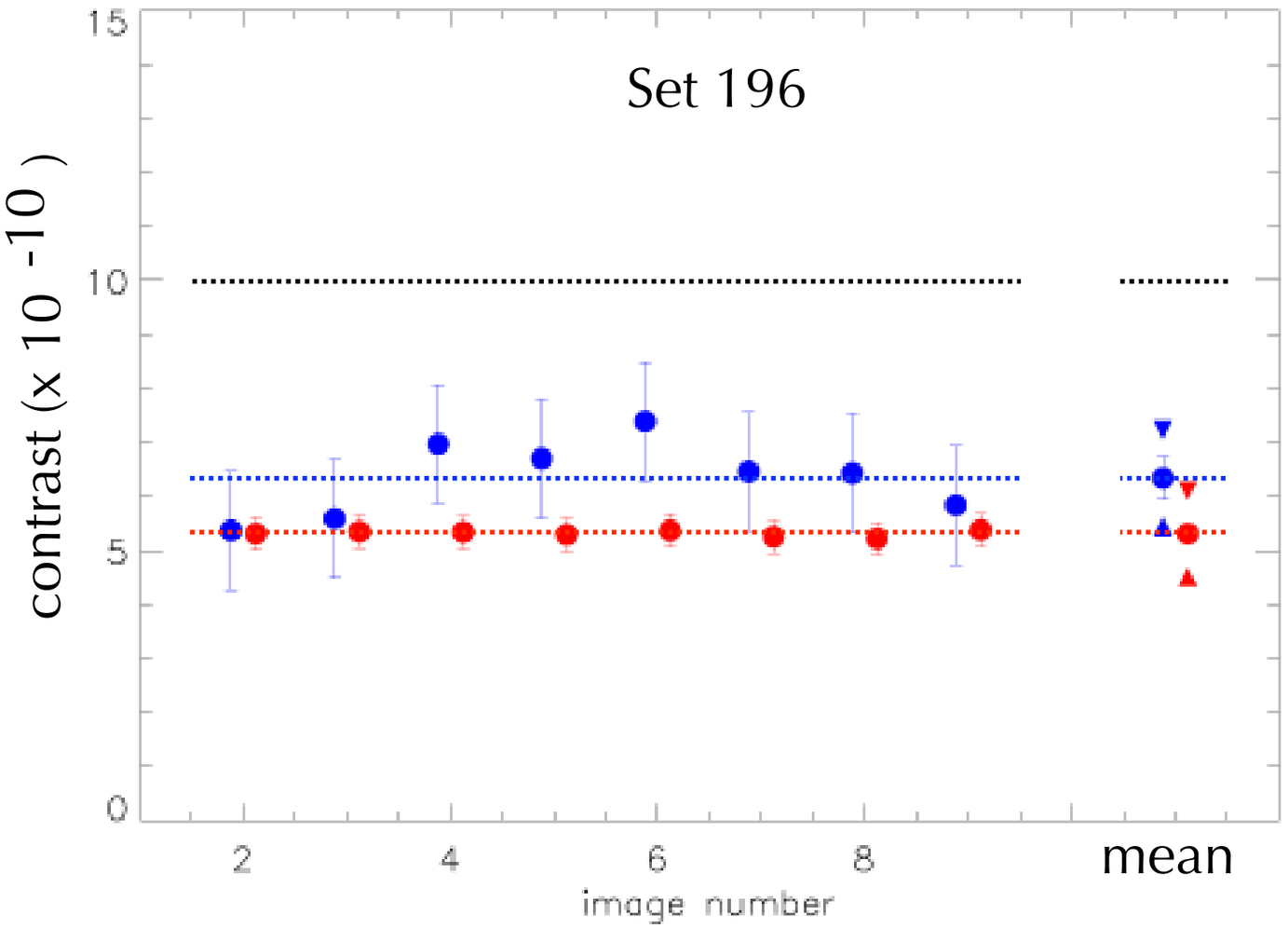


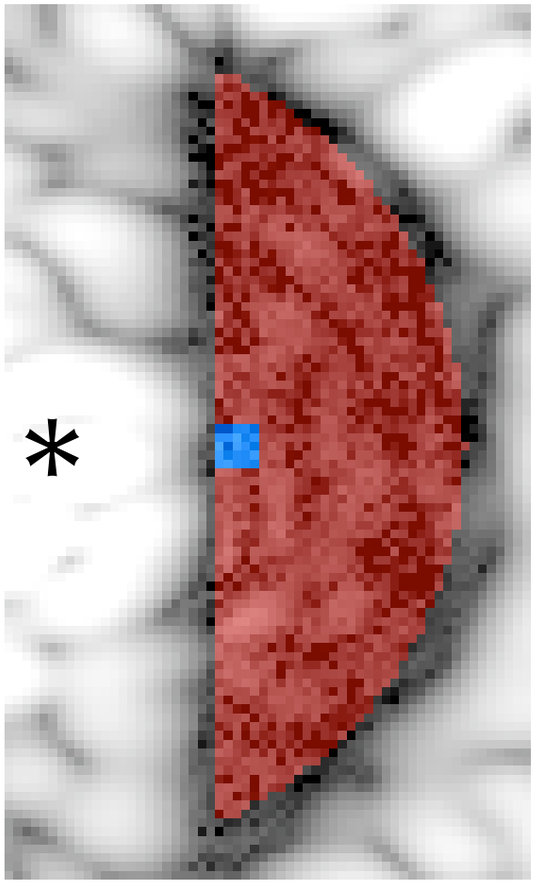
Contrast obtained in a sequence of images over a representative one-hour period. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted "star". Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. One-σ error bars indicate the measurement noise estimated from pairwise data.

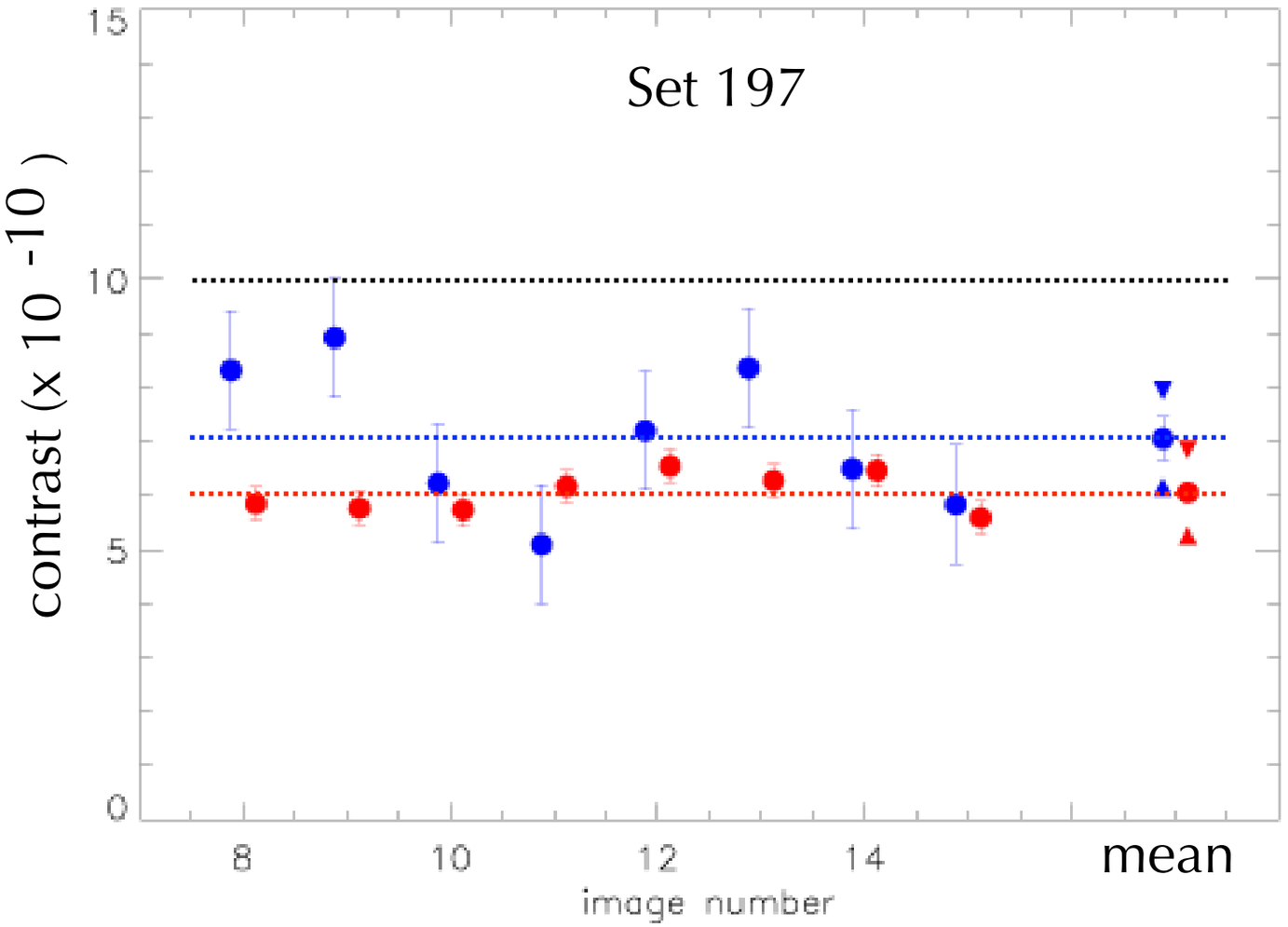



Set 191
contrast (x 10 -10)
15
10
5
0
36
38
40
42
44
mean
image number




Set 196
contrast (x 10 -10)
15
10
5
0
2
4
6
8
mean
image number

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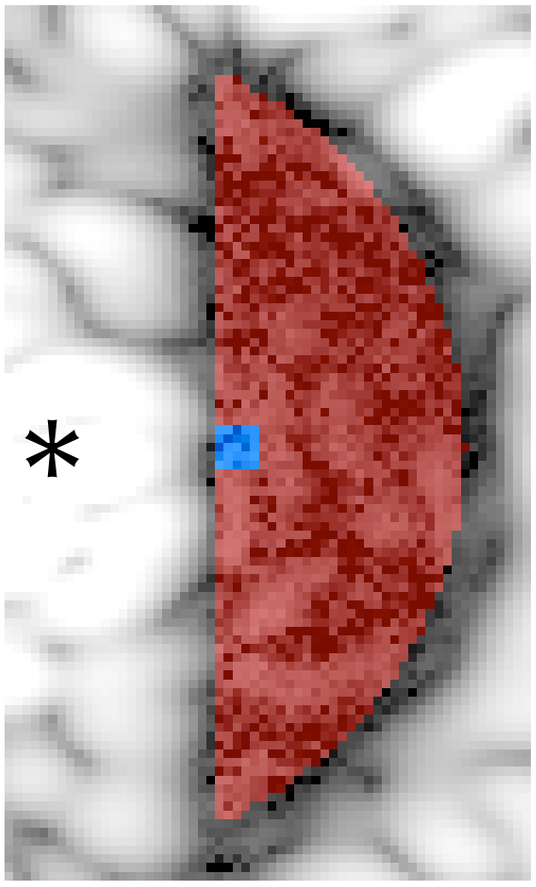
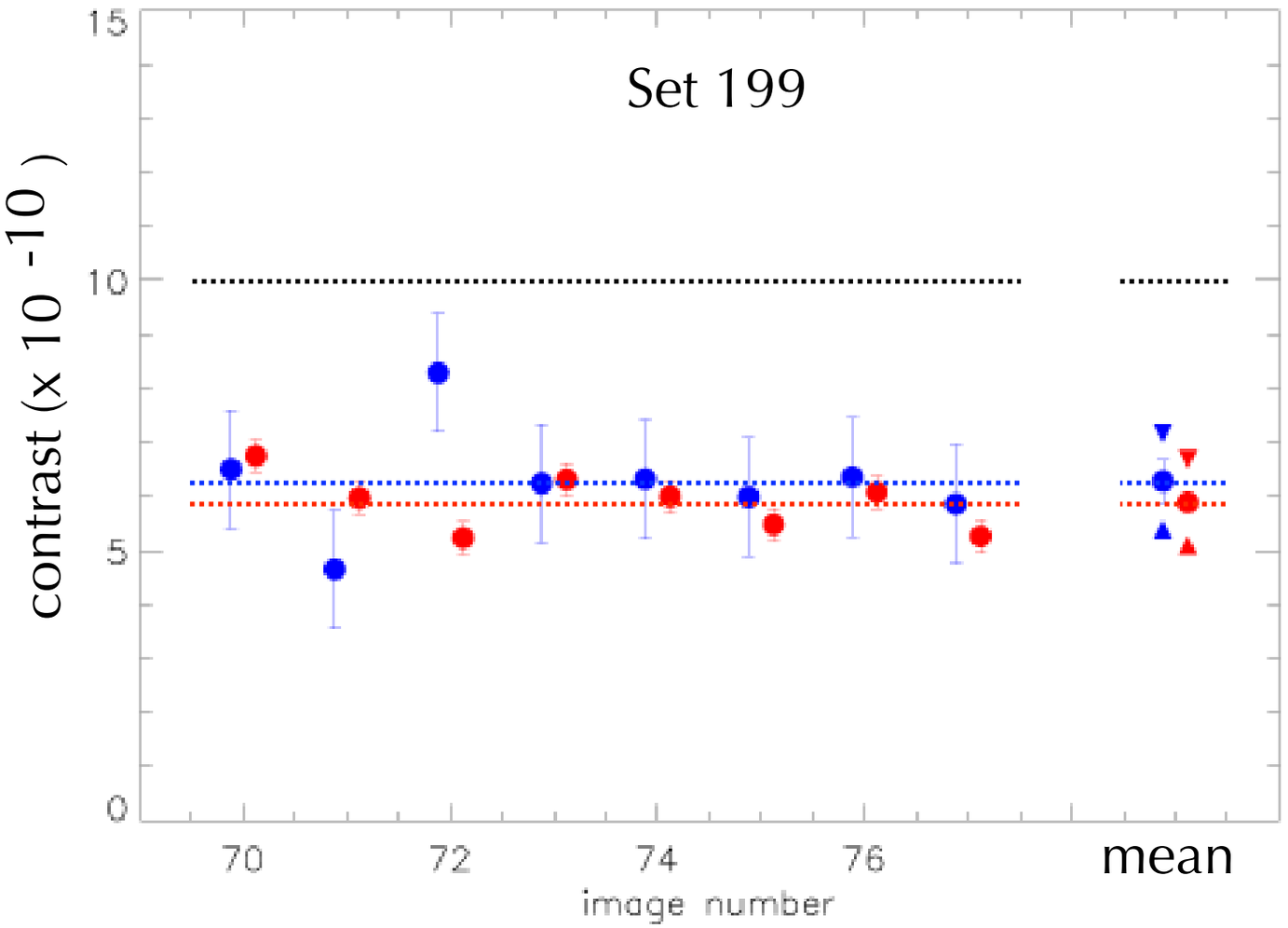
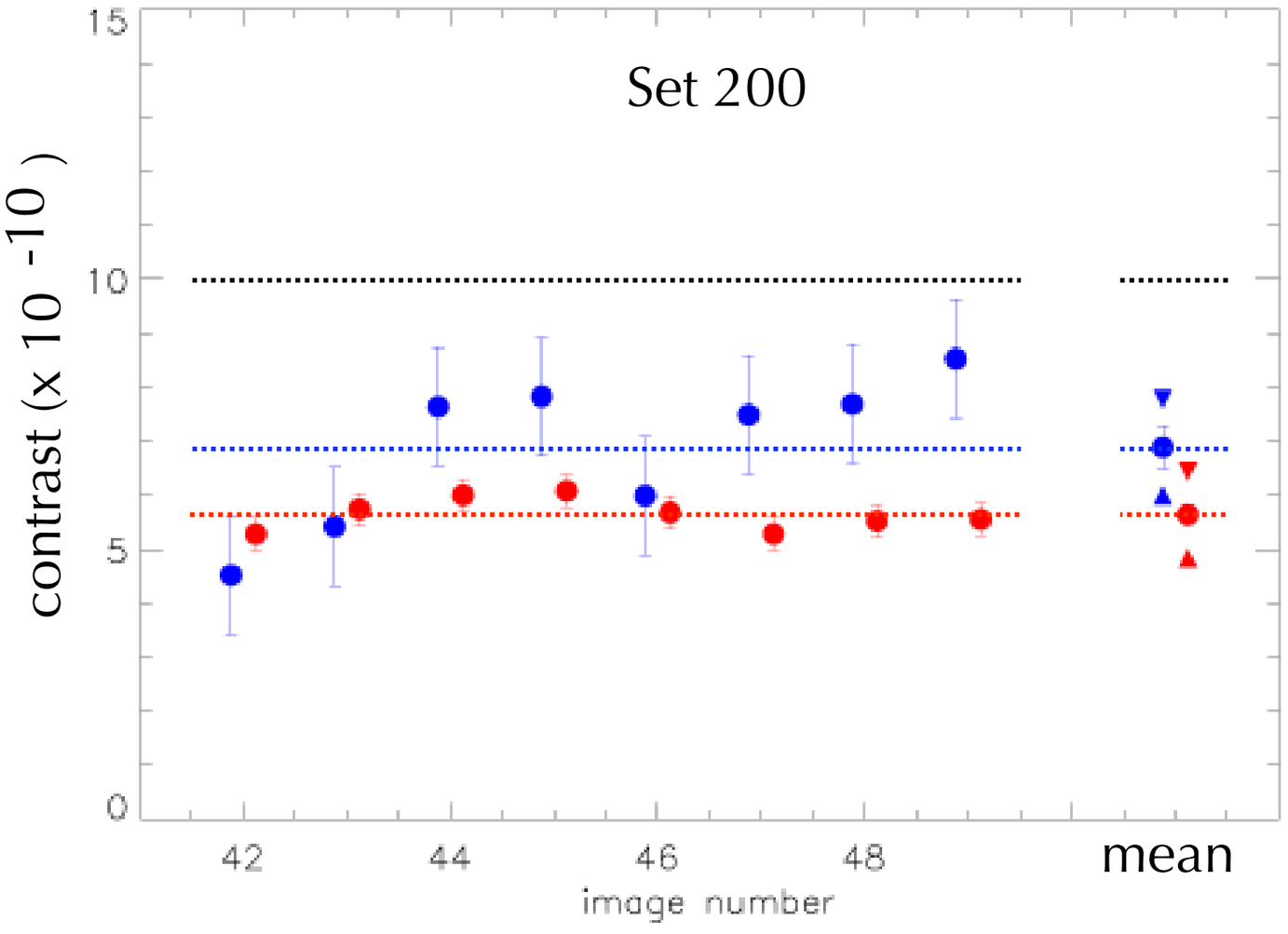
contrast (x 10 -10)
15
10
5
0
8
10
12
14
mean
image number

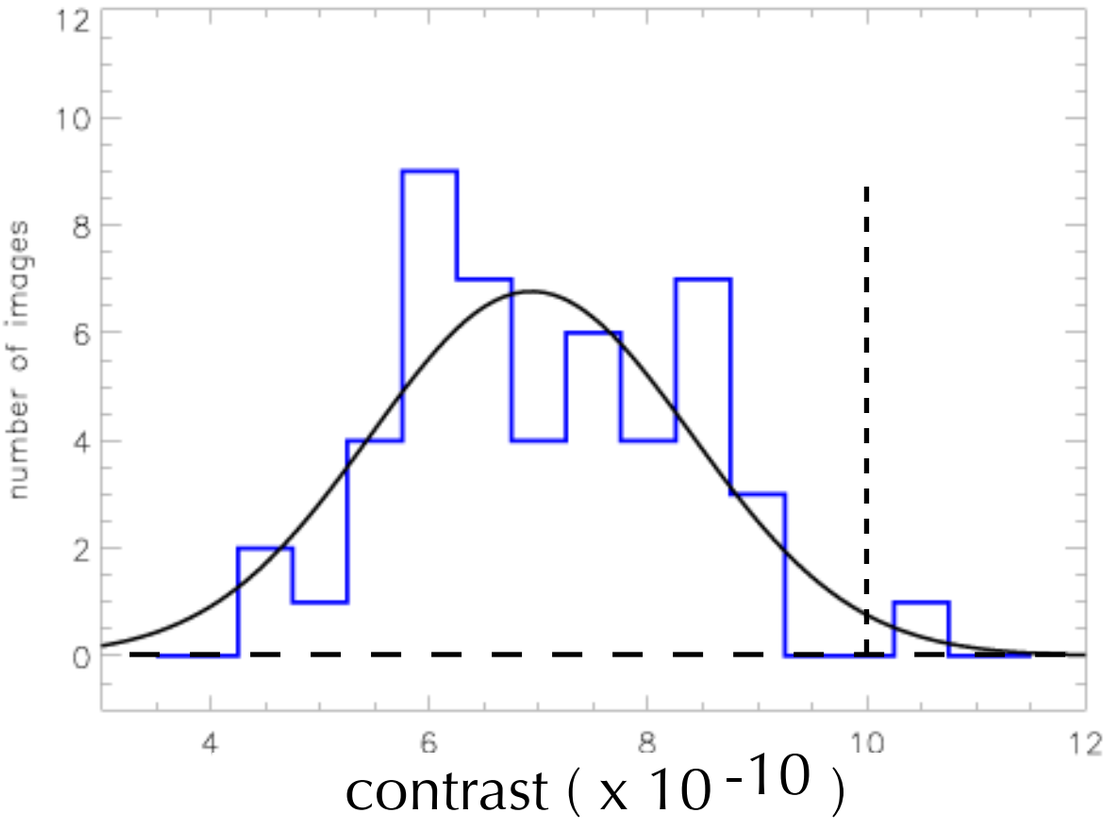



Set 199
contrast (x 10 -10)
15
10
5
0
70
72
74
76
mean
image number

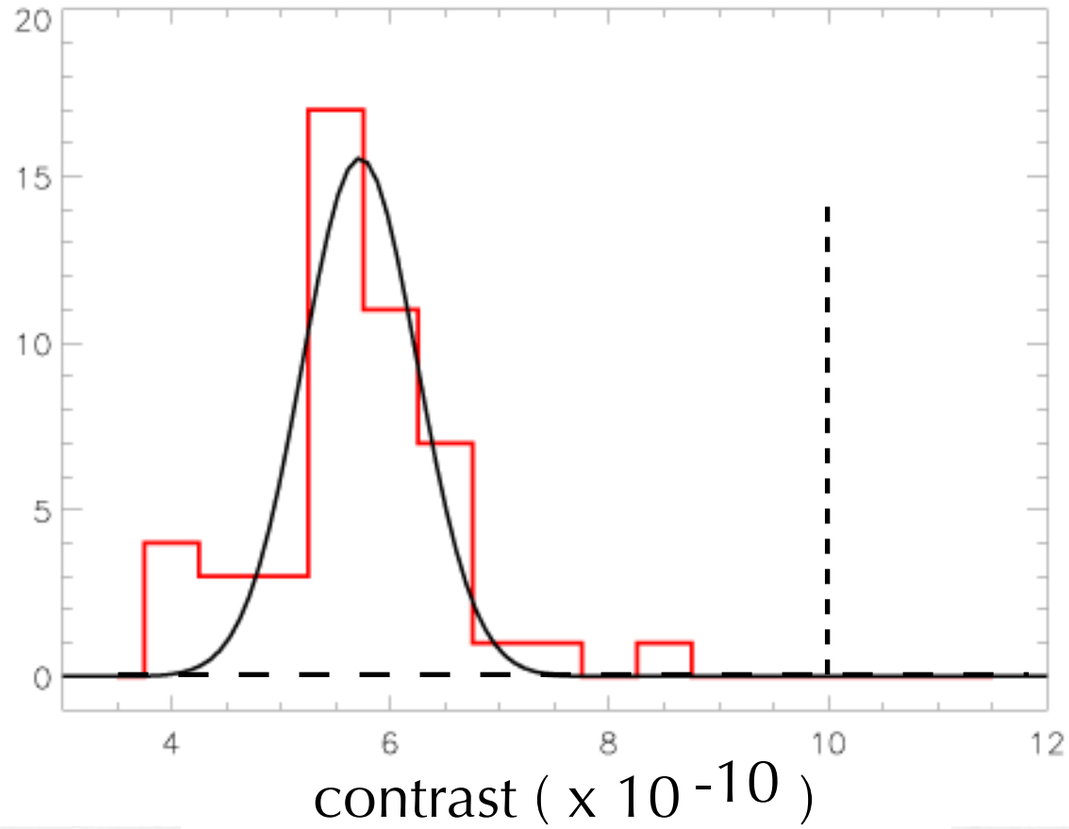

Set 200
contrast (x 10 -10)
15
10
5
0
42
44
46
48
mean
image number

Repeatability of contrast in a sequence of data sets

Inner 4-5 λ/D

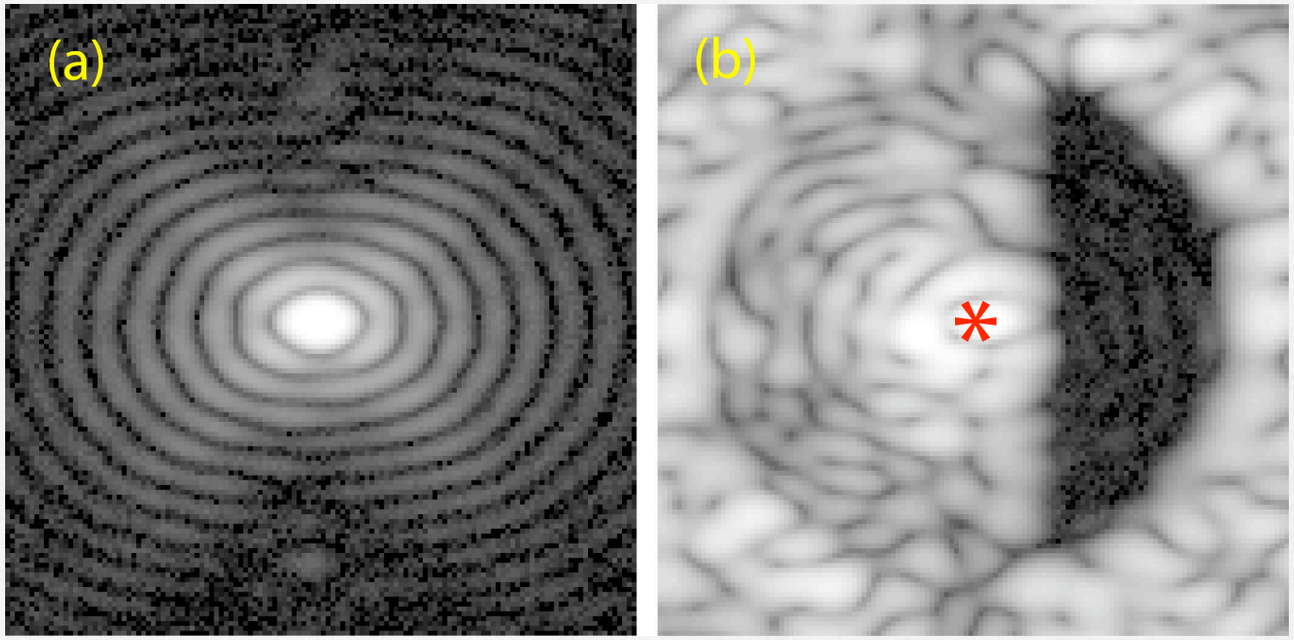


Outer 4-10 λ/D



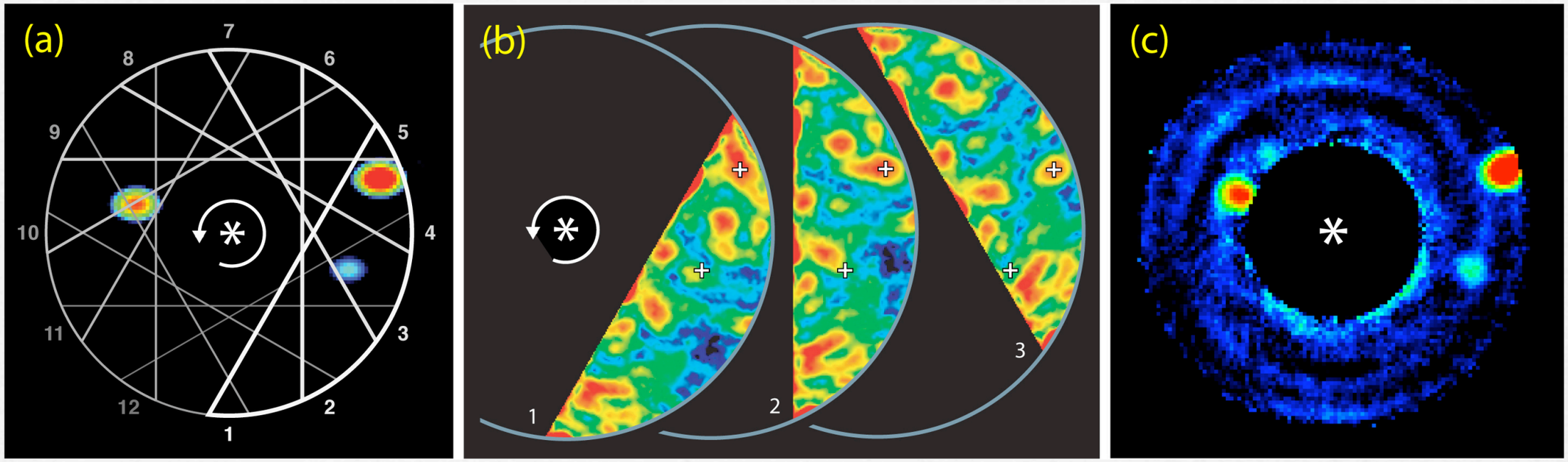
Summary of contrast measured during six different hour-long data sets (distributed over one week) in the inner and outer high contrast fields (again in blue and red respectively), indicates mean contrasts of 6.9 and 5.7 x10-10 respectively.

Open-loop stability of the HCIT dark field



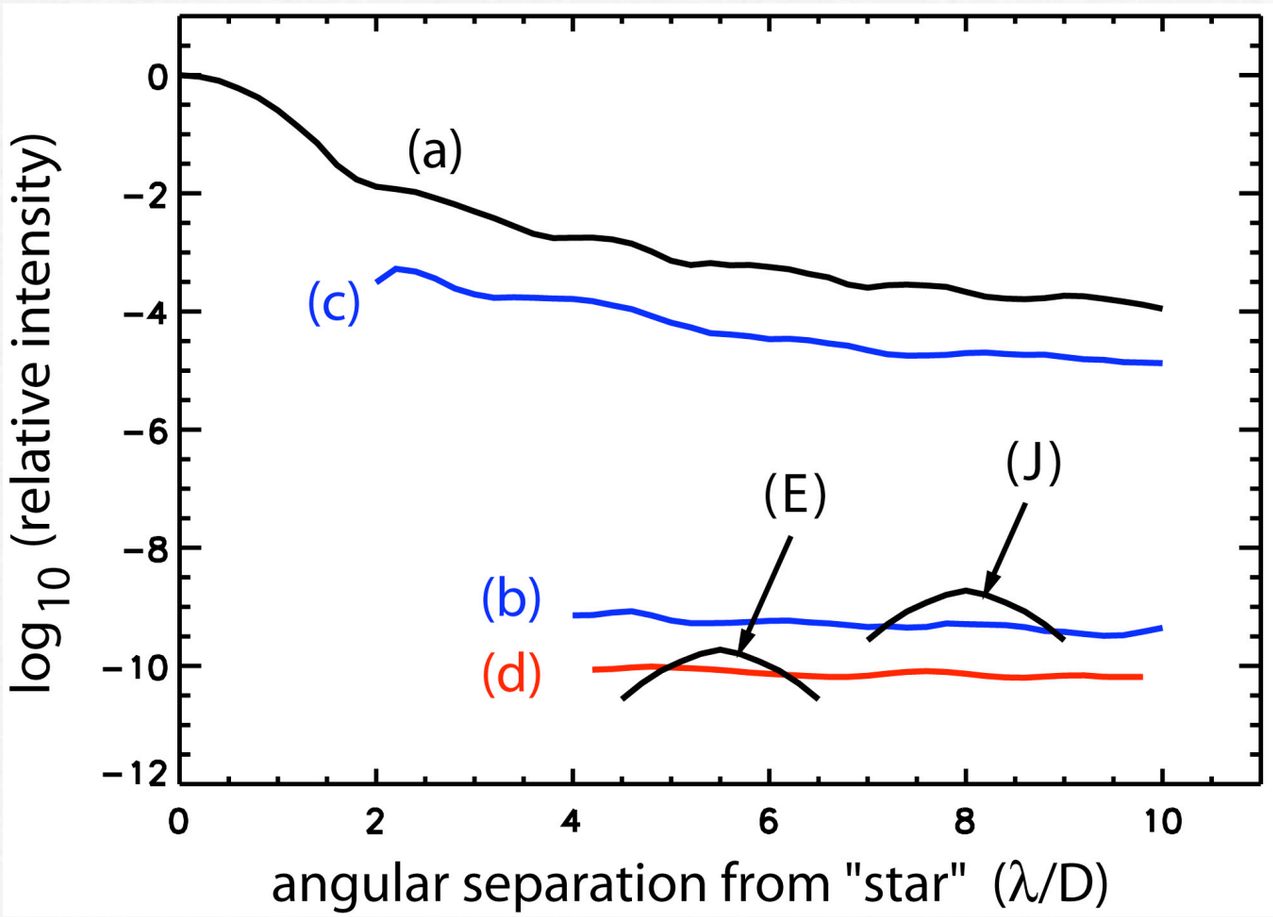
HCIT coronagraph PSFs: (a) the star with focal plane mask removed and Lyot mask in place; and (b) the dark half-field with DM voltages set initially by speckle nulling.

Demonstration of roll deconvolution on HCIT data



Simulation of roll deconvolution with a sequence of 480 consecutive HCIT images taken open-loop over a period of five hours. (a) Three “planets” with the star PSF, but reduced to relative intensities of 10, 5, and 1x10-10. Rotation of the “telescope” and the D-shaped dark field is indicated by the wire grid. (b) Three of the rotated fields are shown, with the simulated planets superimposed (crosses). The 480 images were segregated into 48 sets of 10, and used to construct 48 fields rotated in 7.5 degree increments. (c) The result of roll deconvolution on the set of 48 images by John Krist. The nominal Earth (4 o’clock) and Jupiter (2 o’clock) are clearly seen.

Coronagraph PSF comparison, including roll deconvolution



Comparison of azimuthally averaged PSFs of (a) the star, with focal plane mask offset and Lyot stop in place; (c) the coronagraph field with all DM actuators set to equal voltages; (b) the coronagraph with DM set for a dark half-field; and (d) the result of simulated roll deconvolution with the set of 480 consecutive coronagraph images.
PSFs of a nominal Earth (E) and Jupiter (J) are also indicated.

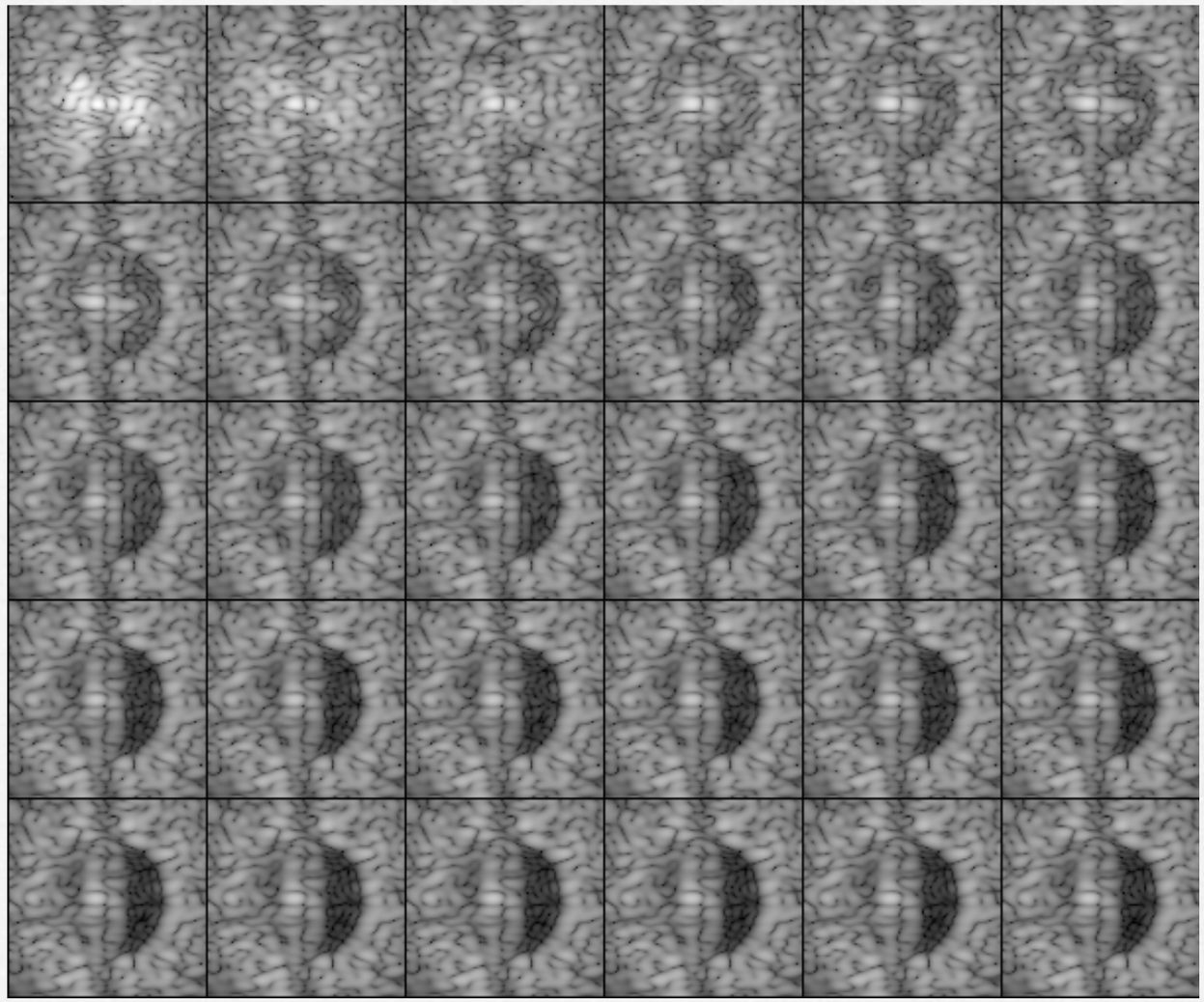
Recent HCIT Lyot coronagraph demonstrations

- Demonstrations of 6x10-10 contrast in narrowband light
  - Direct measurement of contrast in coronagraph images
  - Repeatable contrast (TPF-C Milestone #1 demonstration)
  - Stable contrast (open loop demonstration for 5 hours)
- Speckle nulling algorithm used for wavefront sensing and control
- Close agreement with Fresnel propagation models and speckle nulling models
- End-to-end demonstration, no assumptions on performance of missing components

What next for HCIT?

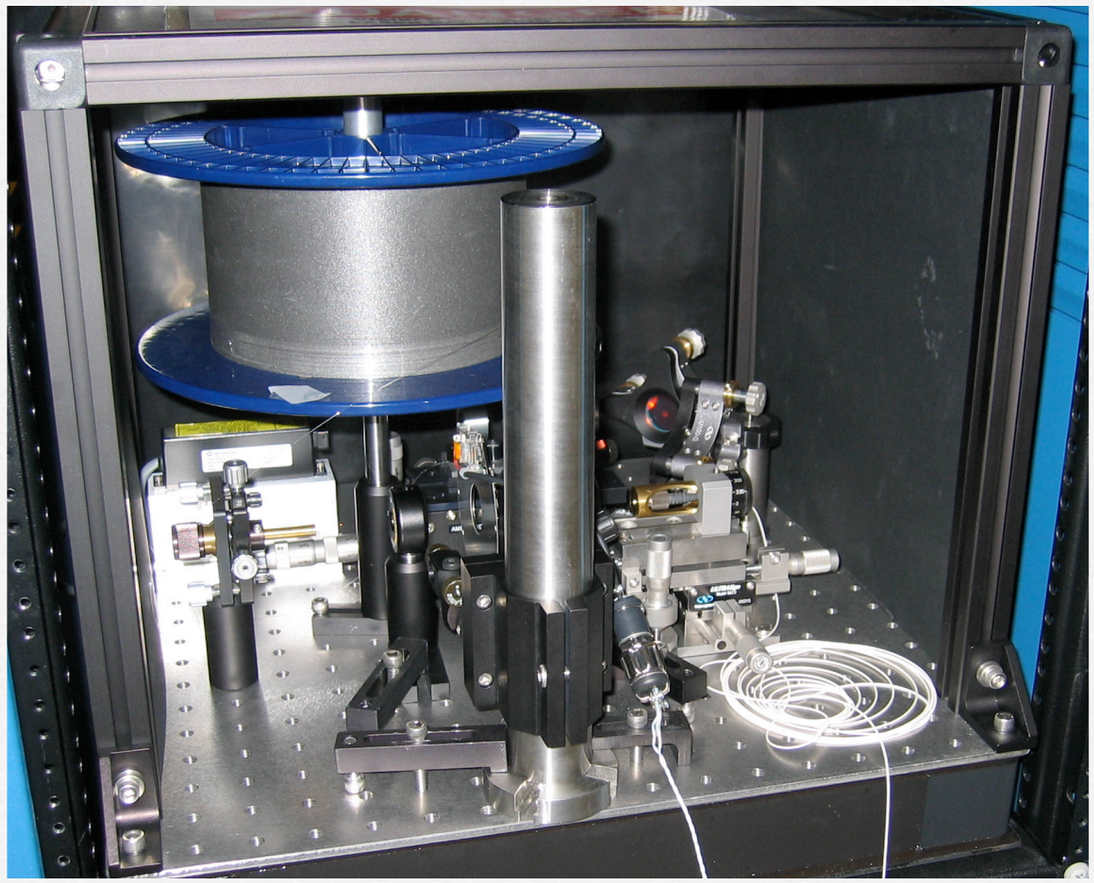
- DM electronics: New multiplexer electronics completed, benefit from lessons learned.
- WFSC algorithms: New algorithms and DM calibration.
- Broad band contrast: supercontinuum source, optical filters: 2%, 10% bandwidth.
- Occulting masks: adjustments for increasing bandwidth.
- Architecture with two sequential DMs: algorithms and new optics.

Speckle nulling developments



Computer simulation of a dark-half field solution with a single DM, with the Borde-Traub algorithm as implemented by John Krist. Contrast converges from scratch to better than 10-9 in less than 24 iterations in monochromatic light.

White light experiments use a supercontinuum white light source



HCIT laser pumped supercontinuum source is used for broadband (white) light.

Intensity is uniform within 10% over the a 600-900 nm spectral range.

Filter complement includes 2%, 10%, and 20% optical filter bandpasses centered on and around 633 nm and 800 nm.

Intensity is at least 50 times greater, and spectrum is flatter, than Xenon lamp used in previous HCIT white light experiments.

This greater intensity improves S/N in high-contrast white-light coronagraph images.

Other experiments ongoing on the HCIT

- Shaped pupil coronagraph (Belikov, Kasdin, Vanderbei / Princeton)
- Alternate speckle nulling algorithms (Borde-Traub, Krist, Kern)
- Spectral discrimination imaging (Biller, Close / U. of Arizona)

End